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Stirrup forces during approach, take-off and landing in horses jumping 70cm

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ABSTRACT

Stirrups aid the rider to stabilise their lower leg allowing it to be used effectively for communication and in maintaining their position in the saddle. Relatively few studies have investigated stirrup forces and to the best our knowledge no studies have reported stirrup forces in jumping. The aim of the present study was to measure stirrup forces in five showjumping horses ridden by the same professional rider. All horses were in regular training and competition jumping at least 30cm higher than the fence used for the study. The fence chosen was a 70cm upright with a pole at the top and a groundline. Right and left stirrup forces were measured using wireless load cells placed between the stirrup leathers and the stirrup. The signals were transmitted and digitised at 100Hz and synchronised with video from a webcam using an inertial measurement unit. After warming-up, including over jumps, each horse attempted the jump three times from each rein in canter (3 horses left then right rein; 2 horses right then left rein). Mean peak total (sum of left and right) stirrup force for the approach (n=5 strides per horse per jump), take-off and landing phase of the jump was 1034±110, 1042±284 and 1447±256N (range 905 to 1815N), respectively (mean±sd). There was no significant difference between right or left mean peak stirrup force during approach or take-off, but mean peak force was consistently higher on the right stirrup during the early phase of landing on either the right or left rein (Right: 827±320N; Left: 615±336N; $P<0.05$). In conclusion, the mean total peak stirrup forces measured in the present study in the same rider jumping five different horses over a 70cm single upright fence are similar to previous reports of peak stirrup forces in gallop and consistent with observations of asymmetric loading of the saddle and horses' backs by riders.

KEYWORDS: showjumping; equestrian; biomechanics; asymmetry; rider

INTRODUCTION

Stirrups have been used for at least 2,000 years to improve the rider's balance and stability in the saddle, particularly during warfare. More recently, stirrup design has changed and diversified to meet the needs of different types of riding but, on the whole, the general design of stirrups has not changed. Stirrups support the "weight" of the rider's legs (Kang *et al*., 2010) and may also be used to convey signals to the horse through distribution of the rider's body weight and stabilizing the lower leg and foot during the application of leg aids. Riders can distribute their bodyweight between their seat in the saddle and their feet in the stirrups. When sitting riders apply most of their bodyweight and force through the seat, with less force in the stirrups (Stapley et al., 2020). In contrast, during rising trot and in the forward or jump-seat position, where the rider's body is suspended above the saddle, their bodyweight is supported through the legs into the stirrups, resulting in periods when essentially all the force of the rider is transmitted to the horse through the stirrups. Lateral distribution of the rider bodyweight, through the stirrups, can also be used as a directional aid for the horse (Powers and Harrison, 2002). It is essential for the rider to be balanced to be synchronized with the horse's locomotion and to enable them to transmit clear and effective aids to the horse during riding to prevent inconsistent application of aids that can generate conflict behaviors (Waran and Randle, 2017). Despite the stirrups being a key are of interaction between the horse and rider, there is a paucity of research into stirrup forces during riding (Stapley *et al*., 2020; Randle *et al*., 2017). An increased understanding of how riders interact with stirrups as a fundamental piece of equipment is needed to inform equitation practice (Williams and Tabor, 2017). Technology has a key role to advance equitation theory practice by allowing the measurement behind traditional riding goals such as being able to 'shifting weight' as an aid to the horse (Randle *et al*., 2017) and facilitating an evidence based approach within equitation (Waran and Randle, 2017).

The position and balance of the show jumping rider has considerable influence on their horse's jumping performance (Powers and Harrison, 2002; Klimke, 1989). During showjumping, horse and rider experience vertical and horizontal displacement across the approach, suspension and landing phases of the jump (Clayton *et al*., 1995). The position of the rider during the jump will affect the horse's centre of pressure, angular momentum and velocity, and therefore the clearance over a fence (Powers and Harrison, 2004; Clayton *et al.,* 1995). Stability of the rider will be influenced by stirrup leather length and the security of the foot in the stirrup. Shorter stirrup leather length in particular, as used in racing and jumping, are associated with greater flexion of the rider's hip, knee and ankle joints (Hyun and Ryew, 2015), which can then act as springs to support the body weight during galloping and jumping where the rider is "out of the saddle" (i.e. the rider's buttocks are not in contact with the saddle). Jockeys support most of their body weight in the stirrups and adjust the flexion angles of the hip, knee and ankle joints to absorb the horse's vertical oscillations (Walker *et al*., 2016). Similarly, in eventing and showjumping, riders place the majority of their weight through the stirrups as opposed to through their buttocks and the saddle. Understanding how riders use their stirrups during jumping and comparing the results to their use in symmetrical and asymmetrical gaits will further understanding of how they impact rider and horse performance and welfare (Stapley *et al*., 2020; Randle *et al*., 2017).

Relatively few studies have investigated stirrup forces during horse riding. Bye and Lewis (2020) reported peak stirrups forces for left and right stirrups on a mechanical horse of the order of 149N & 130N at sitting trot and 423N and 417N at rising trot, respectively. The original data were presented as % bodymass but have been estimated in N from the mean weight of the riders. The apparent symmetry between left and right stirrup forces is unsurprising given that mechanical horses move symmetrically and do not turn or bend through the neck in the same way that a real horse does. Martin et al. (2016) measured stirrup forces during rising trot for one elite rider across three horses during flatwork. They found the force pattern of the stirrup load showed two peaks per stride cycle, corresponding to the phases of the trot. Peak forces were higher during the rising phase of the trot and lower when the rider was sitting, reporting maximal loads of 7.4±1.6 N/kg and 7.5N±1.0 N/kg and 2.3N±0.9 N/kg and 3.1N±1.0 N/kg for right and left stirrups, in rising and sitting trot respectively. The stirrup forces measured during the rising phase were close to the pressures recorded under the horses saddle simultaneously (Martin et al., 2016).

Van Beek *et al.*(2012) measured stirrup forces in 23 riders riding 5 different horses and reported mean peak total forces (i.e. sum of left and right peak force) of 286N at sitting trot and 739N at rising trot. These are very similar to the total forces reported by Bye and Lewis (2020) of 279N and 840N for sitting and rising trot, respectively. This similarity between the mechanical horse and the live horse suggests, at least at trot which is a low speed gait, the vertical motion and hence stirrup force is predominantly generated by the rider. Stapley et al. (2020) measured stirrup forces across different stirrup designs: flexible, flexible-rotational and fixed traditional stirrups, in for four riders of mixed experience levels. While they found no significant differences in stirrup forces, there was a trend for increased loading in the rider's outside stirrup and the highest forces occurred during the rising phase of the trot.

Walker *et al.et al.*(2016) investigated stirrup forces at gallop on live racehorses and on a simulator. In agreement with Bye and Lewis (2020) and van Beek *et al.*(2012), they found that stirrup forces were symmetrical at gallop on the simulator, but on the live horse at gallop peak forces were asymmetric and higher on the opposite side to the lead limb (Walker *et al.*2016). Walker *et al.*(2016) did not report total stirrup forces, but rather stirrup force amplitude i.e. the difference between the minimum and maximum stirrup force during a stride cycle. The baseline force on the live horses was ~125N whilst on the simulator it was ~200N (Figure 1; Walker *et al.*2016). If this is added to the reported amplitudes this would approximate the absolute peak stirrup forces, equating to 322N and 320N (total peak force 642N) for the left and right stirrups respectively at gallop on the simulator, and 707N and 748N (1455N) for the left and right stirrups respectively at gallop on the live horse. The mass of jockeys was not reported, but on Figure 1 (Walker *et al.*2016), 50% of the jockey weight was given as ~270N, so equivalent to 540N (55kg). If the total peak force at gallop in both stirrups was 1455N, this suggests that the acceleration due to gravity was 1455N/540N, equivalent to ~2.7g. This also assumes all weight was in the stirrups.

Using the same system to measure stirrup forces as in the present study, stirrup forces of 570N (right) and 750N (left), 1320N in total, have been measured for a Thoroughbred racehorse in a right lead fast canter (Marlin, unpublished observation), consistent with the data of Walker *et al.*(2016).

As far as we are aware, at the time of writing, there are no published studies describing stirrup forces during showjumping. The present study was undertaken to investigate stirrup forces before, during and following a 70cm jump consisting of a single upright jump.

MATERIALS AND METHODS

The study was carried out in an outdoor arena 40m x 30m with a sand and fibre surface. The arena was fine-harrowed and rolled prior to the study. All horses had been training and jumping on this surface for at least 6 months and were housed in stables next to the arena. On the day of the study there was minimal wind, it was partly sunny and the air temperature was 18-22°C. All horses were owned and ridden by the same professional rider who was one of the authors (SH) and who was competing at British National level (male, 33 years, 83kg, 188cm tall) and was right-handed. The rider was instructed to select stirrup lengths the same on the left and right side but to adjust them as he felt appropriate for each horse and the height of the jump.

Animals

The characteristics of the horses used in the study are shown in Table 1. All animals were in regular training, considered orthopaedically sound and the exercise used was consistent with their normal training and management.

Table 1. Characteristics of horses used in the study.

Horses	Sex	Age (years)	Height (hands)	Breed	Previous Jumping Level (cm)	Current Jumping Level (cm)
BA	Gelding	16	16.0	Irish Sport Horse	135	100
WE	Gelding	14	17.3	KWPN	145	130
CH	Gelding	5	17.3	Oldenburg	110	110
OL	Mare	6	16.3	Anglo-European Sport Horse	120	120
DU	Gelding	8	16.2	Irish Sport Horse	110	110

Equipment

Left and right stirrup forces were recorded using a pair of low-profile load cells with a range of -5000 to 5000N (DDE-5000N-002-000, Applied Measurements Ltd, Aldermaston, Berkshire, RG7 8PN, UK). The load cell was connected between the stirrup leathers and the stirrup using a custom welded steel metal connector consisting of a steel loop (45mm x 20mm OD; 35mm x 9mm ID) welded to a steel nut at the top and a two stainless steel

Caribiner snap hooks 50mm long and rated at 120kg each (Figure 1a). The load cell was connected by a 1 metre cable to a wireless strain gauge transmitter with battery power supply (T24-ACMI-SA, Applied Measurements Ltd, Aldermaston, Berkshire, RG7 8PN, UK). When fitted to the horse the load cell and stirrup connectors were covered by a custom leather and Velcro cover to protect both the device and the horse and rider (Figure 1b). Each load cell was supplied with a Traceable National Standards (UK) calibration certificate which covered the full range of the load cell. In addition, on the measurement day the calibration and linearity of each load cell was verified before and after the study by loading with 100kg in 25kg steps. The wireless transmitter units were housed in a small pack attached to the back of the saddle.

Figure 1a: Configuration of load cell and wireless strain gauge transmitter.

Figure 1b: Configuration of load cell and wireless strain gauge transmitter with protective leather cover attached.

The analogue wireless signals from the load cells were received by a wireless receiver unit with a range of 800m and ±10VDC outputs per channel (T24-AO1i, Applied Measurements Ltd, Aldermaston, Berkshire, RG7 8PN, UK). The analogue outputs from the wireless receiver were digitised at 100Hz by a 24-bit A/D convertor (OMB-DAQ-2408-2AO, Omega Engineering Ltd, Manchester, M44 5BD, UK) and the data recorded using DAQami software version 4.2.1f0 (Measurement Computing Corporation, Norton, MA 02766, USA). Recordings were exported as CSV files for further analysis in Microsoft Excel.

The jump was filmed at 90° from a distance of 10m with a webcam at 60fps (c920, Logitech Europe S.A., Lausanne, Switzerland) in order to allow identification of the take-off and landing strides. The video and stirrup data were synchronised using a digital output from the A/D convertor and the PC Clock.

Protocol

Each horse was warmed-up for 10 minutes at walk, trot and canter on both reins. The rider was then instructed to jump the fence 6 times, alternating between reins each time. The rider was then instructed to jump the fence 3 times from the same rein and then to switch and jump 3 times of the other rein. The rider was instructed to jump from a “forward-seat” or “two-point seat” position such that there was minimal if any contact between the rider’s buttocks and the saddle. Three horses were randomly allocated to jump from the left then the right rein and 2 from the right then left. Horses were ridden in canter at all times. The fence consisted of an upright with a pole 2 holes below the top pole and a plank 4 holes below that. A rustic pole was also used as a groundline 50cm from the centre of the jump.

Statistics

For each rein, a mean of the peak stirrup force on the left stirrup and right stirrup was calculated for the final five approach strides, the take-off stride, and the first five strides after landing stride (landing stride = stride 1) for the three attempts on each rein. Data are reported as median±IQR unless otherwise stated.

Data met non-parametric assumptions. Each phase of the jump was considered as an independent event, therefore a series of Kruskall Wallis analyses with post hoc Mann Whitney U tests, evaluated differences between the approach, take-off and landing, for the right and left stirrups respectively. Wilcoxon Signed Rank analyses compared loading in the right and left stirrups for each phase of the jump and for each stride within the approach and landing phases. Significance was set at $P \leq 0.05$. Differences in loading within the approach and landing phase of the jump between strides 1 to 5 for the right and the left stirrups, were also assessed using Friedman’s analyses. Where significant differences were found subsequent post-hoc Wilcoxon Signed Rank tests (Bonferroni adjusted alpha: $P \leq 0.01$) identified where differences occurred across the strides. Kruskal – Wallis analyses tested if differences existed in stirrup pressure across the individual horses used within the study.

RESULTS

All horses completed all jumping attempts without knocking down the poles. Cumulative peak force (sum of left and right peak stirrup forces) across both stirrups was higher during landing than in either the approach ($P = 0.006$) or take-off strides ($P = 0.001$) (Figure 2). Example recordings from horse BA showing the left and right stirrup forces and total stirrup force during the approach, take off, landing, departure away from the jump and transition into walk are shown in Figures 3a and 3b. There was no effect of individual horse within the stirrup pressures measured (P > 0.05).

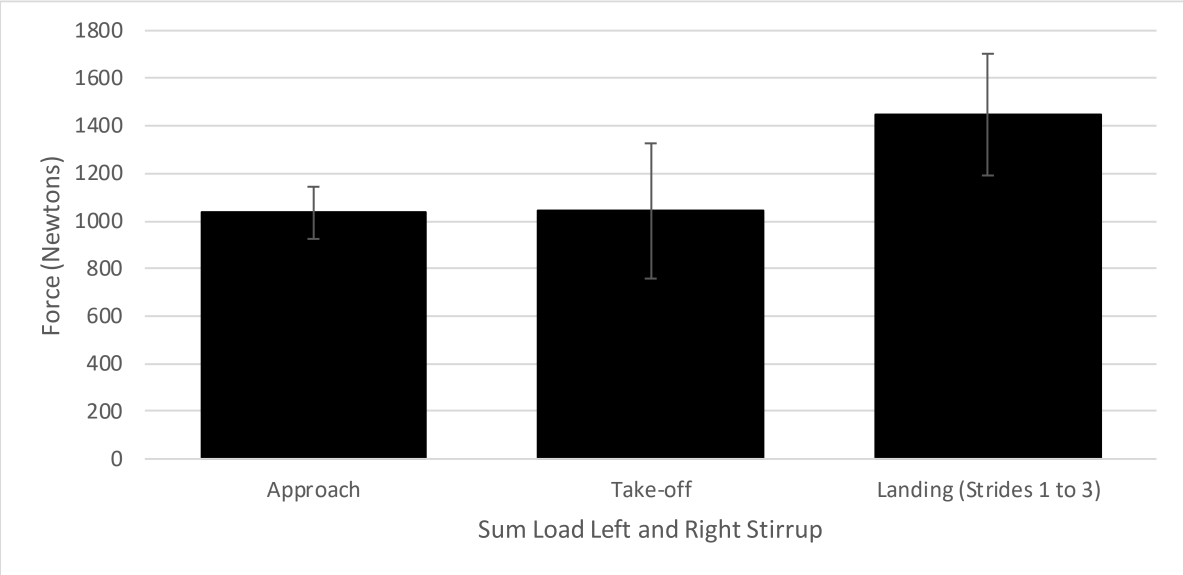

Figure 2: Sum of the peak force (Newtons) on the left and right stirrups during the phases of jumping a 70cm upright fence (median±IQR; n=5 horses).

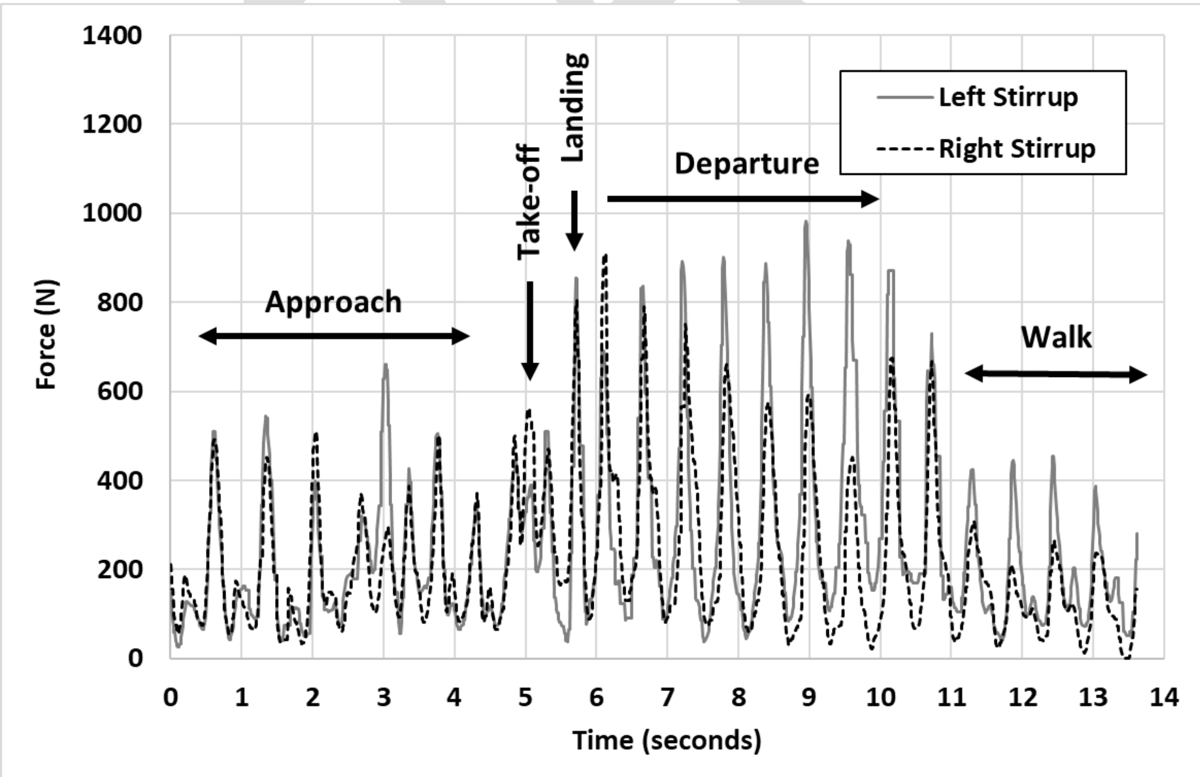

Figure 3a. Example recording of a single jumping attempt from the left rein (Horse BA) showing left and right stirrup forces (Newtons) for the approach, take-off, landing stride, departure away from jump and transition into walk.

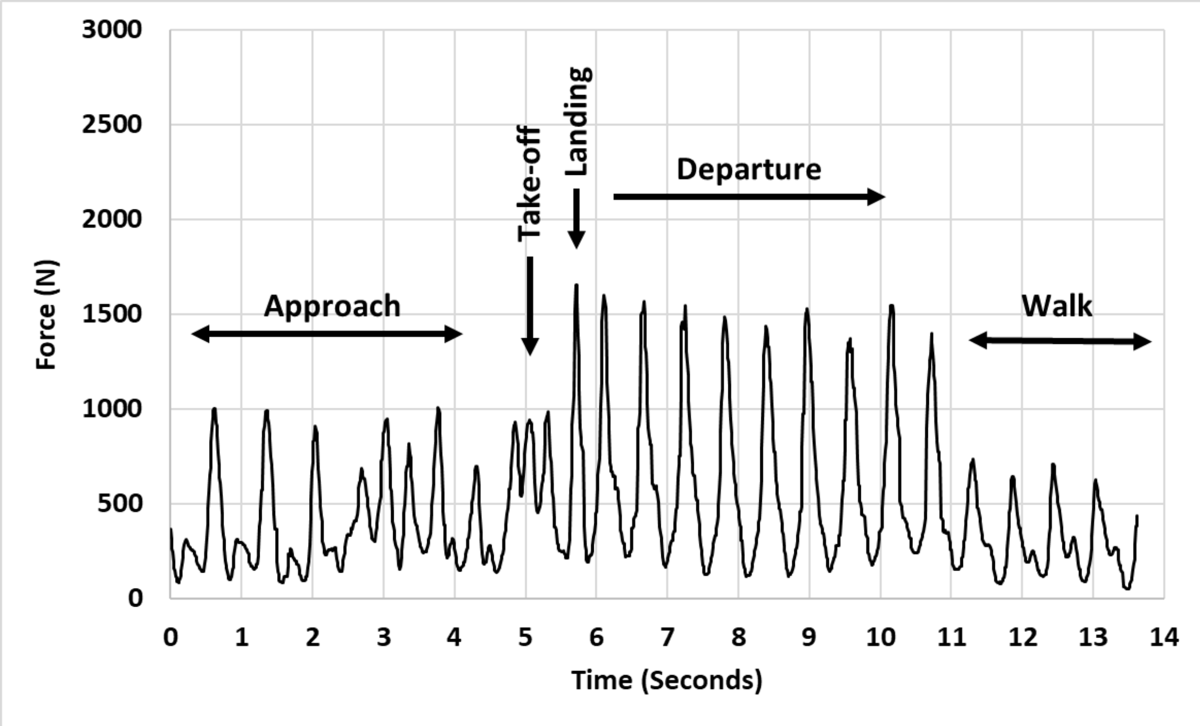

Figure 3b. Example recording of a single jumping attempt from the left rein (Horse BA) showing total (sum of left + right) stirrup force (Newtons) for the approach, take-off, landing stride, departure away from jump and transition into walk.

Differences in right versus left stirrup loading

Across all phases of the jump, the rider loaded his right stirrup 5% more than their left stirrup ($P < 0.005$; Figure 4). No significant differences between right to left stirrup loading were found for the approach or take-off phases of the jump ($P > 0.05$). However, the rider loaded his right stirrup 35% more than his left stirrup during the landing phase of the jump ($P < 0.005$).

Differences in loading also occurred across the phases of the jump for the right stirrup ($P = 0.008$) and the left stirrup ($P = 0.016$). No significant differences existed in loading for riders' left or right stirrups between the approach and take-off stride ($P > 0.05$). Loading was increased by 57% during landing in the right stirrup compared to the approach ($P < 0.0005$), and 61% in the take-off stride ($P < 0.0005$). A similar pattern was observed for the left stirrup with loading significantly increased by 17% during landing compared to the approach (P = 0.029) and by 38% in the take-off stride (P = 0.016).

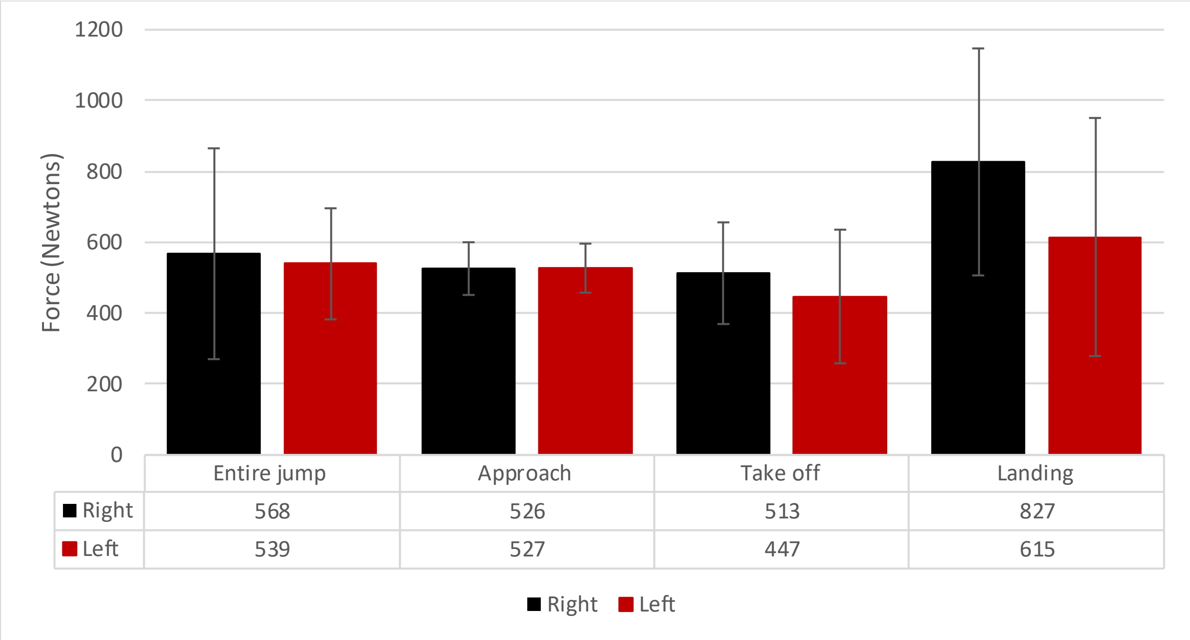

Figure 4: Peak force (Newtons) on the left and right stirrups during different phase of jumping a single 70cm upright fence (Median±IQR; n=5 horses).

In contrast, no significant differences in loading were found across the five strides within the approach (Figure 5) or landing (Figure 6) phases of the jump for either the right or left stirrup (P > 0.05). Across the approach phase, no significant differences occurred in loading for any of the strides in the right or left stirrup or between the right and left stirrup (P > 0.05). However, during landing, increased loads were consistently recorded in the right stirrup compared to the left stirrup, however these were only significant for the first stride (39%; P = 0.021) and the third stride (30%, P = 0.007).

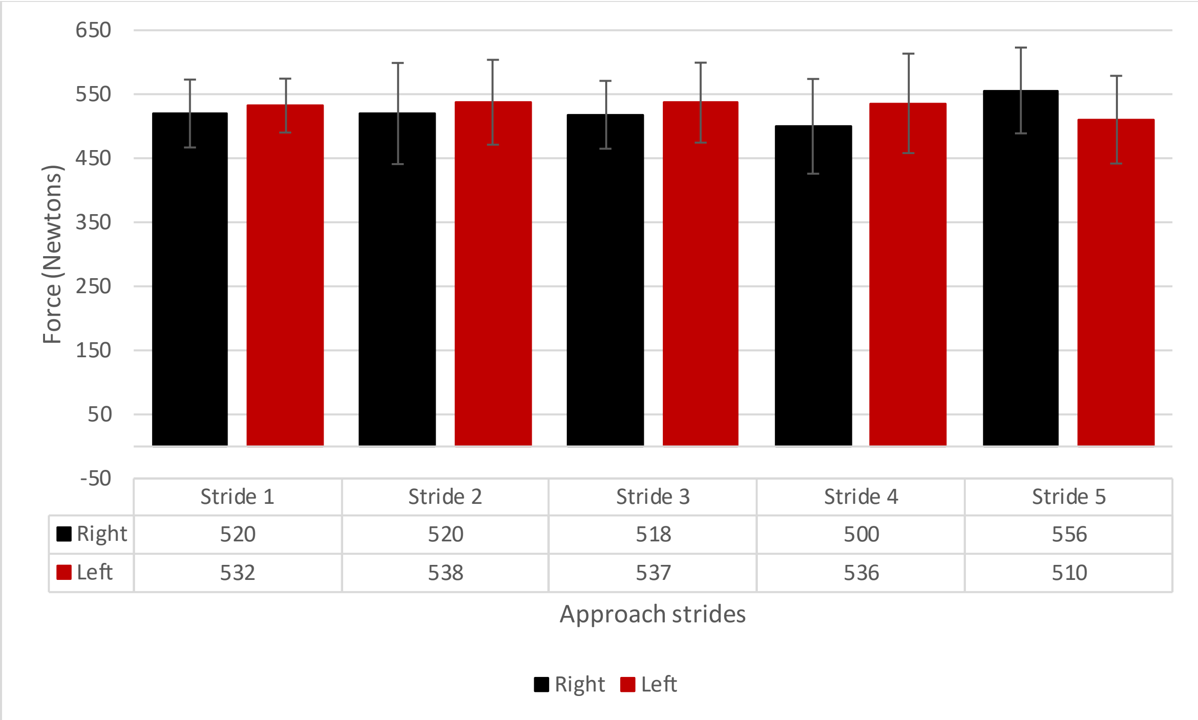

Figure 5: Peak force (Newtons) on the left and right stirrups during approach strides to a 70cm upright fence (Median±IQR; n=5 horses).

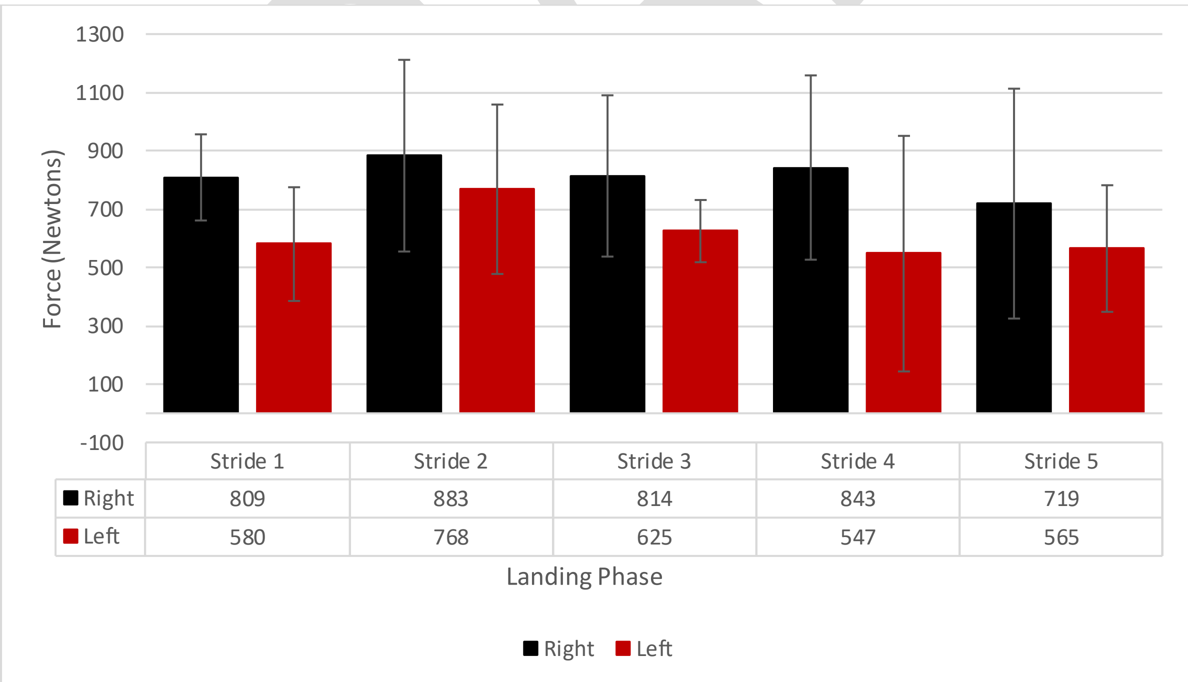

Figure 6: Peak force (Newtons) on the left and right stirrups during landing strides following jumping a 70cm upright fence (Median±IQR).

DISCUSSION

Limitations of the present study.

Although the same rider was used to ride all horses to reduce variation, no attempt was made to assess the symmetry of the rider, who was also one of the authors (SH). Rider asymmetry could lead to asymmetric loading of the stirrups. Similarly, no attempt was made to assess the fit of the saddles. As with rider asymmetry, an asymmetrically fitting saddle could lead to asymmetric loading of the stirrups (Mackechnie-Guire *et al.* 2018).

The median force during canter approach to the fence in the present study was around 1000N. As the rider was in a forward-seat position, we can assume that the 1000N represents the total force acting on the horse. This is consistent with a mean total peak stirrup force for riders in rising trot on a mechanical horse of ~840N (Bye and Lewis, 2020) and 739N on ridden live horses (Van Beek *et al.* 2012). During gallop on live horses, peak total stirrup force was reported to be 1455N (Walker *et al.* 2016), which is again consistent with the present study. The values for canter in the present study are also consistent with a recorded total stirrup force of 1320N for a Thoroughbred racehorse in a right lead fast canter using the same equipment (Marlin, unpublished observation).

Paterson *et al.* (2010) measured limb acceleration in riders jumping horses over a 1.2m jump and reported peak deceleration on landing ranging from 3.4g for an experienced rider on an experienced horse to as high as 3.9g for an inexperienced rider on an inexperienced horse. The bodymass of the riders was not reported unfortunately, but assuming 70kg this would approximate a peak total stirrup force on landing of 2300-2600N. This is 60-70% higher than the peak total stirrup force measured in the present study on landing for a jump 60% lower. Peak total stirrup force on landing from canter over a 70cm jump in the present study (median 1450 N) is also similar to the total stirrup load of a racehorse galloping with a 55kg jockey (Walker *et al.* 2016). In the present study there was no significant difference between peak left or peak right stirrup force in the approach or take-off phases, but there was on landing with the right being consistently higher, irrespective of whether the horse then progressed to a right or left turn at the end of the arena. This effect is therefore likely related to the fact that the rider was right-side dominant. This observation may have important consequences for long-term (horse) back health if this is a phenomenon that exists more widely.

It is surprising that given the fundamental role of the stirrups in maintaining rider stability and allowing the rider to both change position and to use their legs more effectively, that there has been such limited investigation of stirrup function.

The total peak stirrup forces measured in the present study in a rider jumping five different horses over a 70cm single upright fence are consistent with previous reports of stirrup forces in walk, trot, canter and gallop and consistent with observations of asymmetric loading of the saddle and horses' backs by riders. Further work is required to confirm whether the asymmetric peak stirrup forces observed on landing in the present study are due to rider laterality or choice of landing leg, which was not recorded in the present study.

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